

# GAS MIXING EXPERIMENTS IN A LARGE ENCLOSURE

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## ABSTRACT

This paper describes the Large-Scale Gas Mixing Facility (LSGMF) at the Whiteshell Laboratories of AECL and summarizes the results from the first series of gas-mixing experiments. Data are presented in a form suitable for use in code validation. The LSGMF is a 10.3 m x 8.2 m x 11.0 m (length, width, height) concrete enclosure with 0.45-m-thick walls. The internal volume of the test chamber is approximately 1000 m<sup>3</sup>. The large size and the versatile internal volume make this facility ideal for conducting experiments to examine various parameters that can affect the hydrogen distribution in a post-accident reactor containment atmosphere. For safety reasons, helium instead of hydrogen was used in this study. Helium was injected into the facility at the bottom to simulate a break in the primary cooling system inside a reactor containment building. The objective of these experiments was to examine the effects of jet velocity and of an obstruction placed in front of the jet on the subsequent helium distribution. Continuous helium concentration measurements were made at 10 different locations. Results show that because of the height of the facility (11 m), there is sufficient time for the air to entrain into the core of the jet by the buoyancy-induced flow. Dilution of the injected helium reduced the buoyancy force and prevented any strong stratification (high concentration) of helium at the top of the facility. This phenomenon would not be observable if the ceiling of the facility was not sufficiently high.

## INTRODUCTION

During some postulated loss-of-coolant accidents in nuclear power plants, hydrogen may be produced because of metal-steam reactions and subsequently released through a break in the primary heat transport system into the containment atmosphere. This may lead to the formation of a flammable hydrogen-air-steam mixture. The central issue in post-accident hydrogen management in containment is the predictability of hydrogen-steam distribution, whether to support the analyses of hydrogen dilution or to rationalize the number and placement of ignitors [1]. Thus far, hydrogen distribution following an accident is typically analysed using "lumped parameter" codes such as PRESCON and GOTHIC [2]. These codes assume that properties such as temperature, pressure and gas concentration are uniform within a room and are not particularly suited to predict certain key gas-mixing phenomena such as stratification and condensation. In some situations, three-dimensional Computational Fluid Dynamics (CFD) codes may be required to improve the prediction of the distribution of hydrogen in a complex geometry. The latest

version of GOTHIC (GOTHIC 3-D) has such capability. This code has been recently used to analyze various accident scenarios for CANDU reactors.

It is well known that gas-mixing phenomena depend strongly on the scale of the enclosure. The available gas-mixing data are mostly from small-scale experiments [3]. Theory and correlation derived from these data [4] may have high uncertainty when applied to large-scale situations. Most available large-scale tests [5,6] were mainly designed to produce data for validating lumped parameter codes. Information concerning local flow structure and gas concentration were not reported in detail. Data from these tests are not sufficient for validating the state-of-the-art CFD codes such as GOTHIC 3-D. Moreover, validating models for separate effects such as buoyancy-induced or jet momentum-induced mixing require experimental data from well-controlled simple large-scale experiments. These data are currently not available. The objective of this program is to generate a database for the validation of these CFD codes. For this reason, a facility was constructed to examine various gas-mixing phenomena and to generate the database for code validation. This paper describes experimental detail and the results from the first series of experiments performed in the Large-Scale Gas Mixing Facility (LSGMF) to demonstrate the uniqueness and capability of the facility. Data on local helium concentration are presented in a form suitable for use in code validation.

## EXPERIMENTAL APPARATUS

The facility used for this study is the former Shielded Loop Room in the WR-1 Reactor Facility at the Whiteshell Laboratories of AECL. It is a 10.3 m x 8.2 m x 11.0 m concrete enclosure with a wall thickness of 0.45 m and an internal volume of approximately 1000 m<sup>3</sup>. Figure 1 shows a schematic of the facility. Figure 2 shows a perspective sketch of the facility. Helium and steam can be injected into the enclosure at various locations. The maximum flow rates for helium and steam are 9 m<sup>3</sup>/min and 20 m<sup>3</sup>/min respectively. For this series of experiments, steam was not used. Helium was injected into the facility at a constant rate through a 0.05-m or 0.30-m-diameter tube at the bottom (BT) of the facility, as shown in Fig. 1. The axis of the tube was oriented vertically. The helium volume flow rate was set using a calibrated rotameter. The injection velocity was calculated based on the injection tube opening area and confirmed by direct measurement using a turbine meter. The interior of the facility was maintained at atmospheric pressure during the test by venting through exhaust location # 6 (see Fig. 1). It should be noted that exhaust location can affect both the total helium inventory and the flow pattern inside the facility. Because exhaust location #6 is about 1 m from the floor of the facility, it is expected that only air would be vented. As a result, there was no loss of the helium inventory during the duration of the experiment (10 min.). Helium concentrations at different locations inside the facility were monitored by 10 thermal conductivity-type detectors. The probes of these detectors were mounted in two vertically oriented racks. One rack (P1 to P5) was located along the axis of the jet. The other one (P6 to P10) was located at about 2 m from the axis of the jet. Measurements were made by each of the 10 analysers at a frequency of 1 Hz. Data were transferred to a personal computer for analysis.

## RESULTS AND DISCUSSION

It is mentioned earlier that gas-mixing phenomena such as stratification are scale-dependent. The height of the enclosure plays a key role in determining the extent of stratification (defined by the concentration gradient within the enclosure). The higher the ceiling, the longer is the time available for the dilution of the injected gas by air entrainment. It should be pointed that for simulating gas-mixing phenomena in a large enclosure, most computer codes do not model the jet structure in detail. It is often assumed that the injected gas mixes very rapidly with the surrounding air and that the main mechanism for stratification is by buoyancy-induced flow. This assumption ignores the effects of jet velocity on the subsequent gas distribution. To generate data for validating the scaling effects of gas-mixing and the assumptions adopted in computer codes, a series of gas mixing experiments were performed in the Large-Scale Gas Mixing Facility at the Whiteshell Laboratories.

In this series of experiments, three groups of tests were performed: small-jet experiments, large-jet experiments and obstructed-jet experiments. All jets were oriented vertically. The details of the experimental parameters and instrumentation for this series of experiments are summarized in Table 1.

### Experiment with a 5.0-cm-Diameter Jet

Helium was injected into the facility at a constant rate from the bottom injection point (BT) through a tube with a diameter of 0.0508 m, as shown in Fig. 1. The inlet velocity of the helium was 8.6 m/s. In this group of tests, helium concentrations were measured at 10 different locations. The duration of these experiments was 600 s. Helium concentration measurements from these tests are shown in Figs. 3 and 4. Tests were repeated to determine the reproducibility of the data. Results from these tests were found to be within the uncertainty of the measurement themselves.

Helium concentrations measured at different elevations along the axis of the jet (Fig. 3) show that surrounding air was entrained into the core of the jet fairly quickly. Within 3 m from the injection point, the helium concentration was found to be less than 5%. At 5.5 m from the injection point, the average helium concentration was found to be less than 2%. As a result of rapid dilution of the injected helium, stratification of helium near the top of the facility was minimal. Figure 4 shows the helium measurement at about 2 m from the centreline of the jet. The measurement made at an elevation of 10.6 m (P10) shows that helium concentration increased gradually from 1% at 1 minute into the test to about 1.8% at the end of the test (10 min). At the end of the test, the helium concentration in the top half of the facility varied from 1.2% to 1.8%. There was very little helium in the bottom half of the facility. This confirms that there is almost no loss of helium inventory by venting through exhaust #6. This test shows that the extent of stratification in the facility depends on how rapidly the injected fluid is being diluted. The helium concentration at the top of the facility can only be as high as the average helium concentration in the core of the jet at that height. The more the helium dilution, the weaker is the driving force that creates the stratification. With helium injection at the bottom of this facility, which has a height of 11 m, strong stratification of helium

near the top was not observed. Over the duration of the experiment (600 s), the helium concentration at the top of the facility never exceeded 2%.

In the present tests, there are at least two main mechanisms that control the mixing process: jet momentum-induced mixing and buoyancy-induced mixing. With a jet velocity of 8.6 m/s, the jet momentum-induced mixing should play a key role in the vicinity of the jet. It pushed the injected gas deep into the enclosure rapidly. Even though the shear along the jet can entrain air into the core of the jet fairly rapidly, the time available for the entrainment of air to take place is greatly reduced. It is not certain whether high jet velocity can improve the overall mixing process. Because helium is lighter than air, at some point, buoyancy-induced mixing should become dominant. Results from this test alone are not sufficient to determine which is the dominant mechanism for the rapid dilution of the injected fluid.

### Experiment with a 30-cm-Diameter Jet

To examine the effects of jet velocity on the mixing process, an experiment similar to the above was performed with a jet of larger diameter. Helium was added to the facility at the bottom through a cone-shaped device, which has a 0.05-m-diameter nipple at the bottom increasing to 0.305-m-diameter at the other end. The exit end of the cone is 0.8 m from the floor. Fine mesh screens were mounted inside the cone to decrease the mean jet velocity. Keeping the helium flow rate the same as in previous experiments, a jet velocity of 0.24 m/s was achieved. The results from this test are shown in Figs. 5 and 6. Along the axis of the jet, the helium concentrations measured by P1 and P2 were slightly lower than those in the previous small-diameter jet experiment. Concentration measurements from other probes were found to be very similar to the earlier experiments. The observed insensitivity to jet velocity indicates that buoyancy-induced mixing is the dominant mechanism that causes rapid dilution of the jet and controls the subsequent gas distribution inside the facility.

### Obstructed Jet Experiment

The two tests mentioned earlier demonstrated that rapid dilution of the jet fluid with the surrounding air significantly reduces the extent of stratification inside an enclosure. To further demonstrate this point, a 1-m<sup>2</sup> horizontal metal plate was placed 0.45 m above the bottom (BT) injection port. The jet diameter was 0.05 m. Helium was added at the same rate to the facility from the bottom injection port as in previous experiments. Since the jet impinged directly onto the plate, it is reasonable to expect the jet to break up (to lose its coherent structure) completely, allowing the helium to mix with the surrounding air thoroughly in the vicinity of the jet. Helium concentrations measured by the 10 probes are shown in Figs. 7 and 8. Even very close to the jet, the helium concentration (P1) was found to be less than 5%. The helium concentrations were found to be below 2% at other probe locations (Fig. 7). Moreover, measurements from P6 to P10 (2 m from the axis of the jet) also show lower concentrations than those shown in the unobstructed jet test (Fig. 4). The helium was found to spread out more within the facility than it did in the previous experiment. Probes P7 which is 3.57 m from the floor also detected a substantial amount of helium (about 0.6% at the end of the test). As a result, the helium concentration gradient in the facility was decreased. The difference in helium concentrations in

the top half of the facility was found to be less than 0.5%. This test clearly demonstrated that rapid dilution of the injected fluid is an important process tending to minimize stratification effects. This observation provides an important guideline for analysts to set up computer codes to simulate gas mixing in a large enclosure. Using a coarse grid or lumped-parameter approach would imply that the injected gas mixes with the surrounding air instantaneously at the injection point. This tends to under-predict the extent of stratification. This series of tests provides a challenging database for validating the mixing model and the assumptions adopted in containment computer codes

## SUMMARY

The Large-Scale Gas Mixing Facility, which has a height of 11 m and an internal volume of 1000 m<sup>3</sup>, is a facility well suited for examining gas-mixing phenomena. Results from three sets of experiments were reported in this paper to illustrate the capability of the facility. Data show that because of rapid entrainment of air into the core of the jet by the buoyancy-induced flow, the density difference between the jet fluid and the surrounding air also decreases rapidly. As a result, the driving force needed to create a strong stratified layer is reduced. For injection locations at the bottom of the facility, strong stratification of helium near the top of the facility is not observed. Over the duration of the experiment (600 s), the helium concentration at the top of the facility never exceeded 2%. Within the upper 5 m of the facility, the concentration variation was less than 1%. It was also observed that if the mixing process is further enhanced by placing an obstruction in front of the jet causing it to break up and mix with the surrounding air, the extent of stratification is even less. These simple experiments demonstrate the effects of scale in the mixing of gases. These results provide a challenging database for validating the mixing models and the assumptions adopted in containment thermalhydraulic computer codes.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. MENELY D.A., "Hydrogen Management from a Designer's Point of View," OECD/NEA/CSNI Workshop on the Implementation of Hydrogen Mitigation Techniques, Winnipeg, MB, 1996 May 12-16.
2. KRAUSE M. and MATHEW P.M., "Passive Heat Transport in Advanced CANDU Containment," Proceedings of the Third International Conference on Containment Design and Operation, Toronto, ON, Volume 2, 1994 October 19-21.

3. CHEN C.J. and RODI W., "Vertical Turbulent Buoyant Jets - A Review of Experimental Data", Pergamon Press Ltd., 1980.
4. KUMAR R.K., CHIANG H.W. and KALOS F., "Entrainment and Mixing in Vertical Buoyant Light-Gas Plumes", Journal of Energy Resources Technology, vol. 118, p. 77, 1996.
5. "Final Comparison Report on ISP-35: NUPEC Hydrogen Mixing and Distribution Test", OECD Nuclear Energy Agency, OCDE/GD(95)29, 1994, also appears as NEA/CSNI/R(94)29.
6. VALENCIA, L.A. and WOLF L., "Experimental Results of the Large-Scale HDR Hydrogen-Mixing Experiments E11.2 and E11.4", CEC/LAEA/KIAE Seminar on Hydrogen Behaviour and Mitigation in Water-Cooled Nuclear Power Plants, Brussels, 1991.

Table 1:  
Experimental Details for the Helium-Air Mixing Experiments in LSGMF

### Facility Dimensions

Dimensions of main chamber: width 8.2 m, length 10.3 m, height 11.0 m  
Dimensions of auxiliary chamber: width 4.26 m, length 3.5 m, height 4.86 m  
Wall thickness: 0.45 m (reinforced concrete)  
Total volume of LSGMF: 997 m<sup>3</sup>

### Experimental Parameters

Helium flow rate:

- Volumetric flow: 0.0175 m<sup>3</sup>/s
- Mass flow: 2.97 g/s

Jet diameter: 0.0508 m or 0.305 m

Jet velocity: 8.6 m/s or 0.24 m/s

Duration of helium injection: 600 s

Pressure: 100 kPa (constant throughout experiment)

Temperature:

- initial air temperature: 18°C (15 to 20°C)
- initial wall temperature: 18°C (15 to 20°C)
- initial helium temperature: 16°C (15 to 17°C)

### Instrumentation

Injection locations:

- BT: (0.6 m, 4.1 m, 5.1 m)<sup>+</sup>
- LS: (2.74 m, 0.6 m, 5.1 m)
- US: (8.22 m, 0.6 m, 5.1 m)

Exhaust location # 6: (0.79 m, 2.14 m, 0.61 m)

Exhaust opening Area: 0.048 m<sup>2</sup>

Probe locations:

- |                                  |                                 |
|----------------------------------|---------------------------------|
| • P11: ( 1.21 m, 2.05 m, 5.1 m)  | • P12: ( 3.57 m, 2.05 m, 5.1 m) |
| • P13: ( 5.93 m, 2.05 m, 5.1 m)  | • P14: ( 8.29 m, 2.05 m, 5.1 m) |
| • P15: ( 10.65 m, 2.05 m, 5.1 m) | • P1: ( 1.21 m, 4.1 m, 5.1 m)   |
| • P2: ( 3.57 m, 4.1 m, 5.1 m)    | • P3: ( 5.93 m, 4.1 m, 5.1 m)   |
| • P4: ( 8.29 m, 4.1 m, 5.1 m)    | • P5: ( 10.6 m, 4.1 m, 5.1 m)   |
| • P6: ( 1.21 m, 6.15 m, 5.1 m)   | • P7: ( 3.57 m, 6.15 m, 5.1 m)  |
| • P8: ( 5.93 m, 6.15 m, 5.1 m)   | • P9: ( 8.29 m, 6.15 m, 5.1 m)  |
| • P10: ( 10.65 m, 6.15 m, 5.1 m) |                                 |

<sup>+</sup>All locations are indicated by a set of co-ordinates; (measured from the floor, from the south wall, from the east wall).

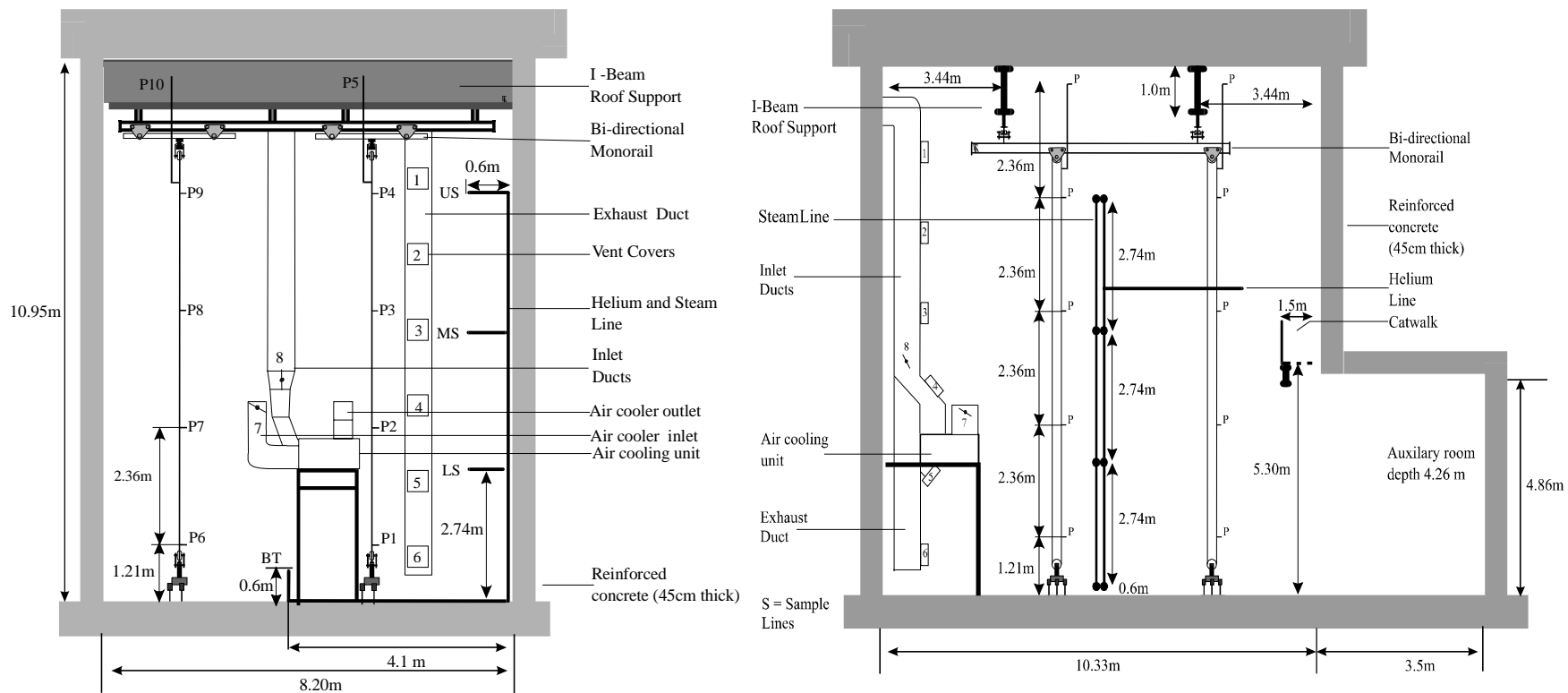


Figure 1: Schematics of the Large-Scale Gas Mixing Facility



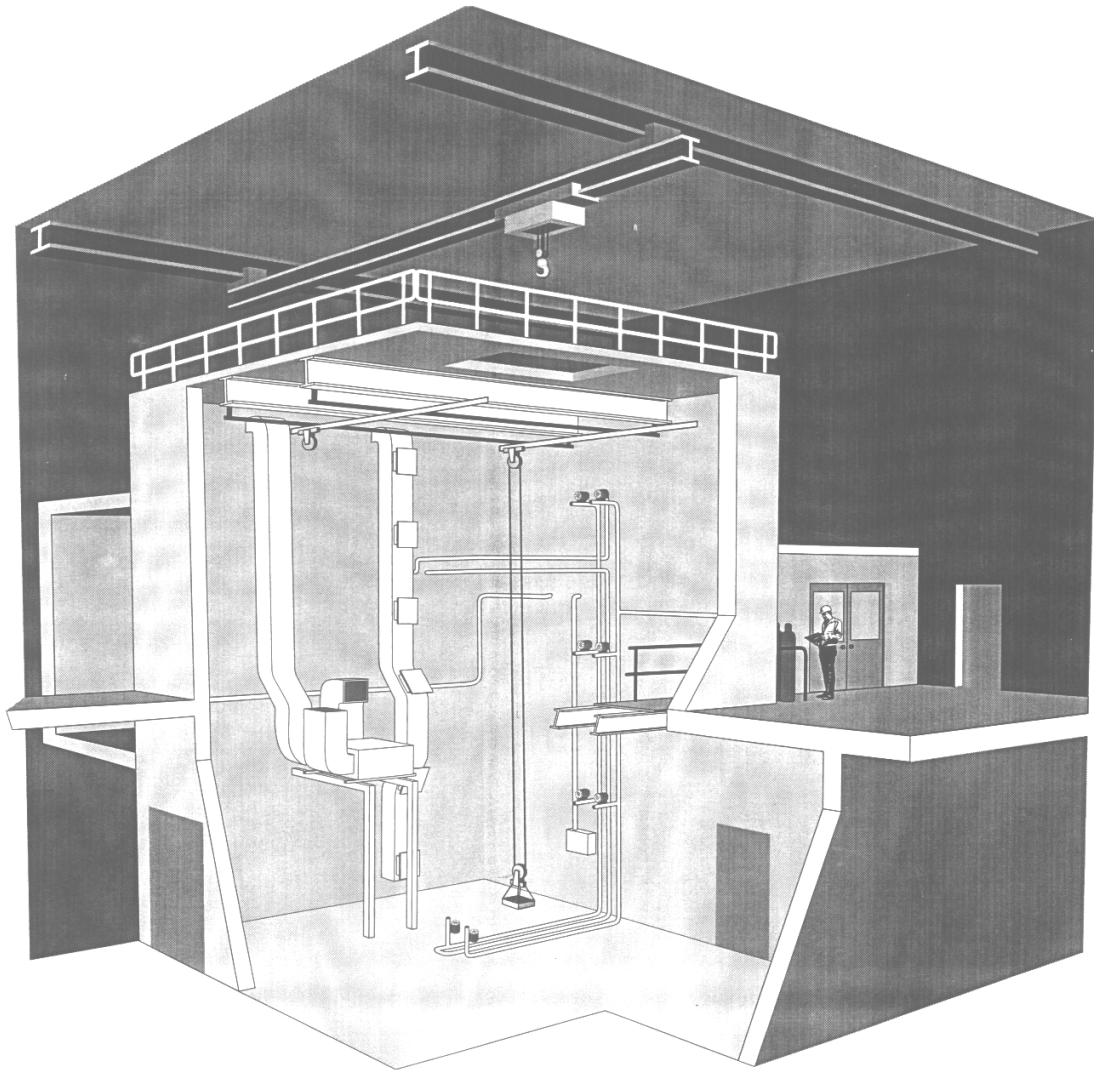


Figure 2: A perspective sketch of the Large-Scale Gas Mixing Facility

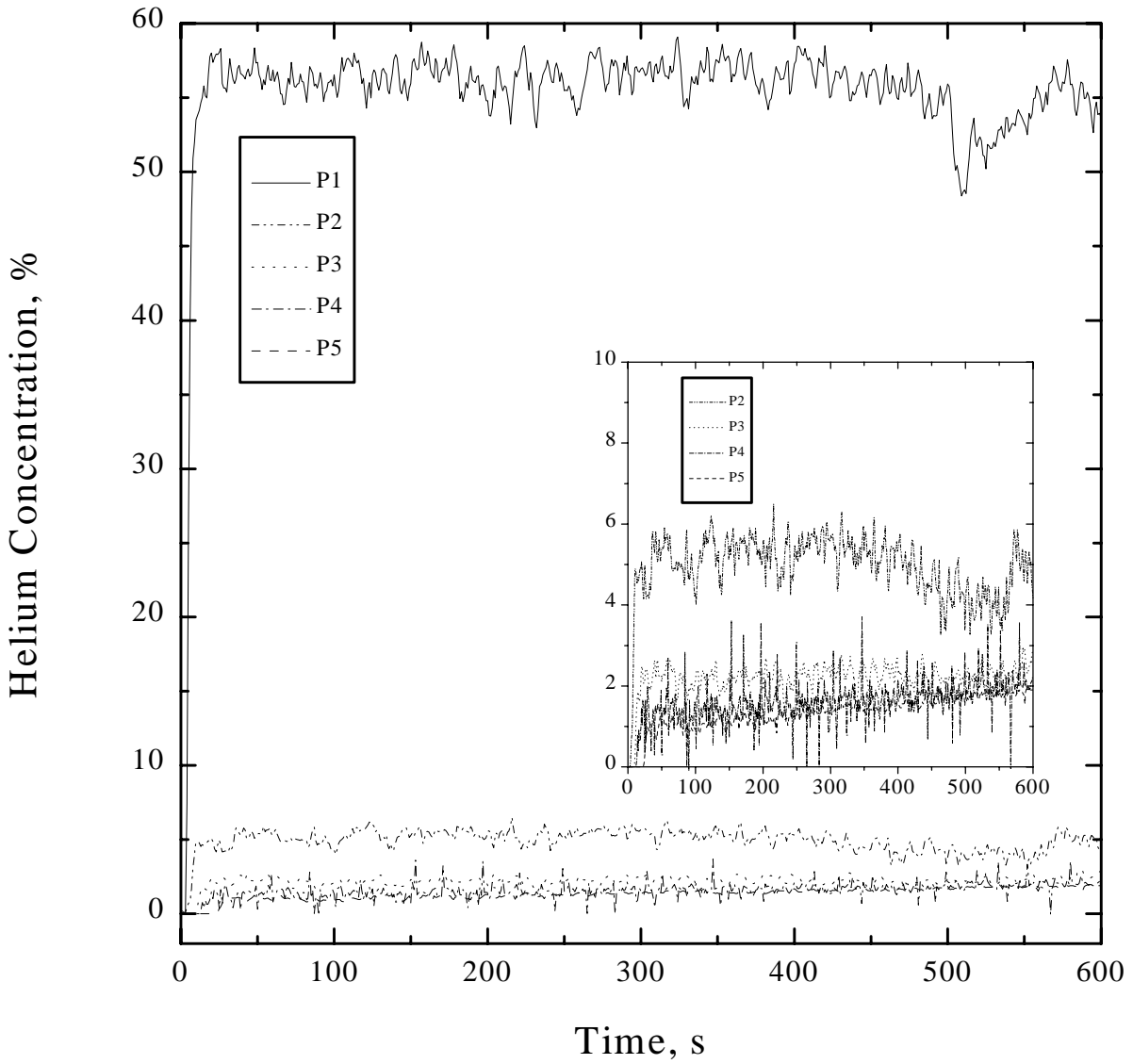


Figure 3: Concentration Measurements from Probes 1-5 for the Continuous Injection of Helium from the Bottom Inlet. (Jet diameter = 0.050 m; jet velocity = 8.6 m/s)

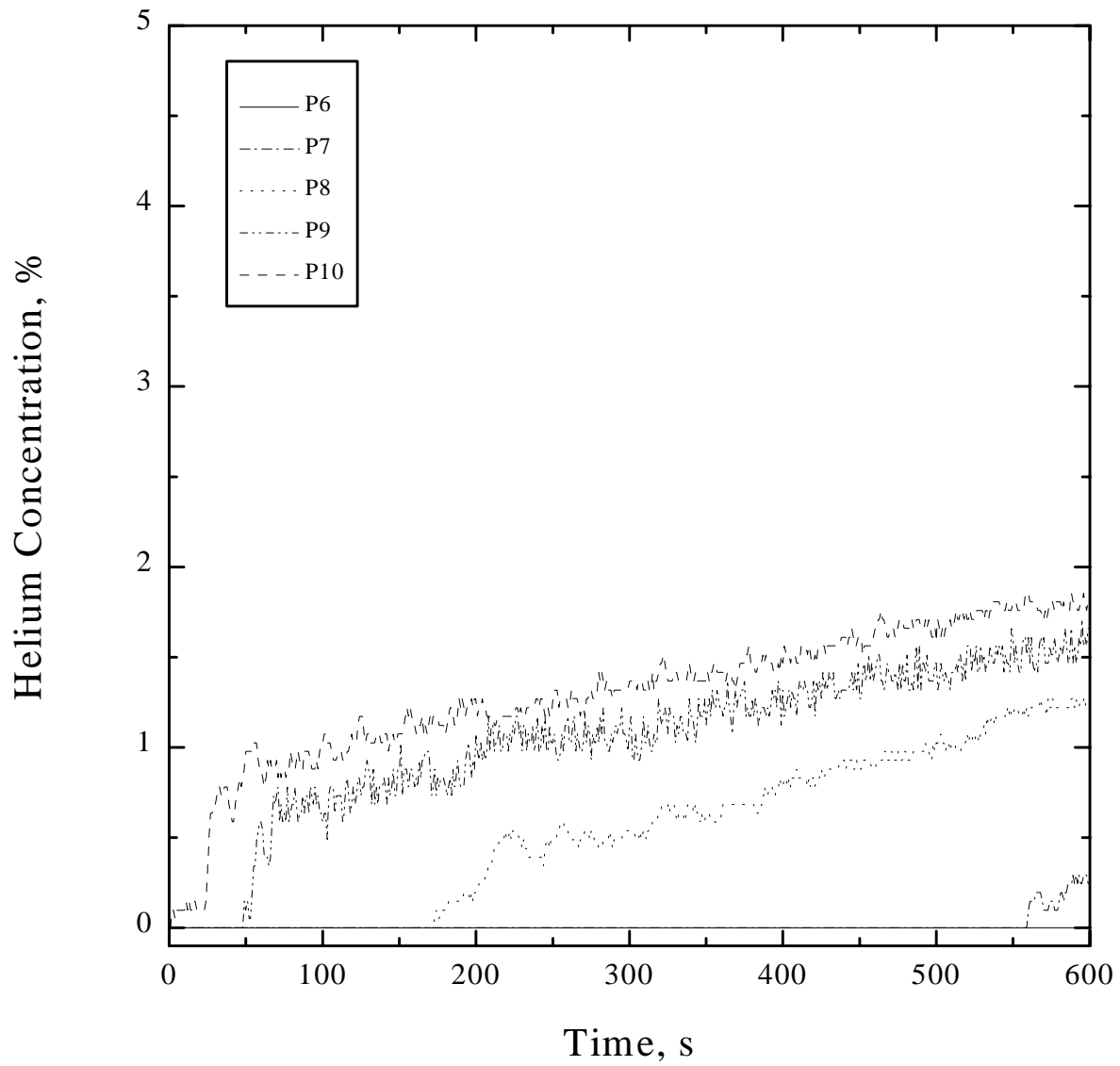


Figure 4: Concentration Measurements from Probes 6-10 for the Continuous Injection of Helium from the Bottom Inlet. (Jet diameter = 0.050 m; jet velocity = 8.6 m/s)

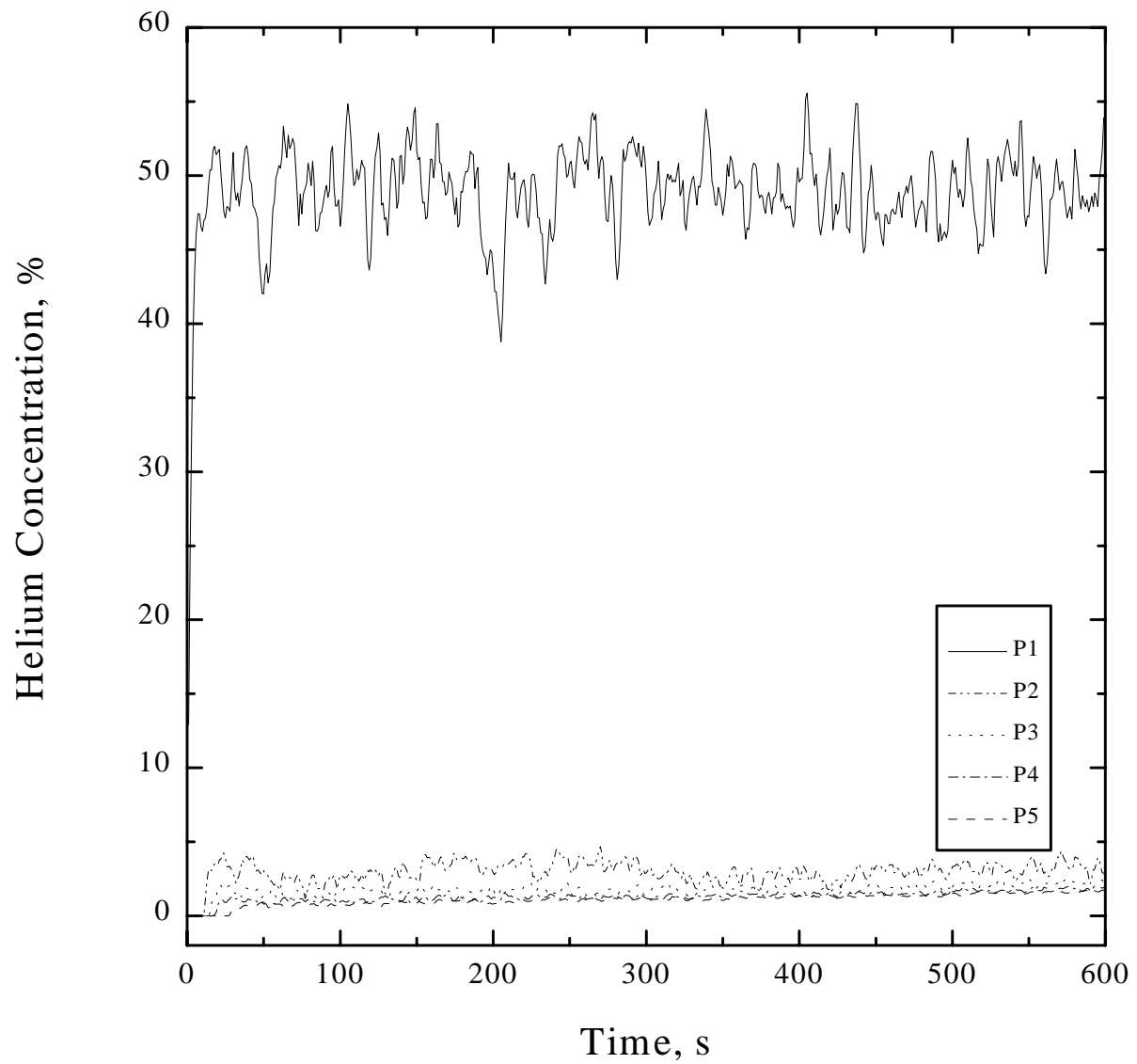


Figure 5: Concentration Measurements from Probes 1-5 for the Continuous Injection of Helium from the Bottom Inlet. (Jet diameter = 0.30 m; jet velocity = 0.24 m/s)

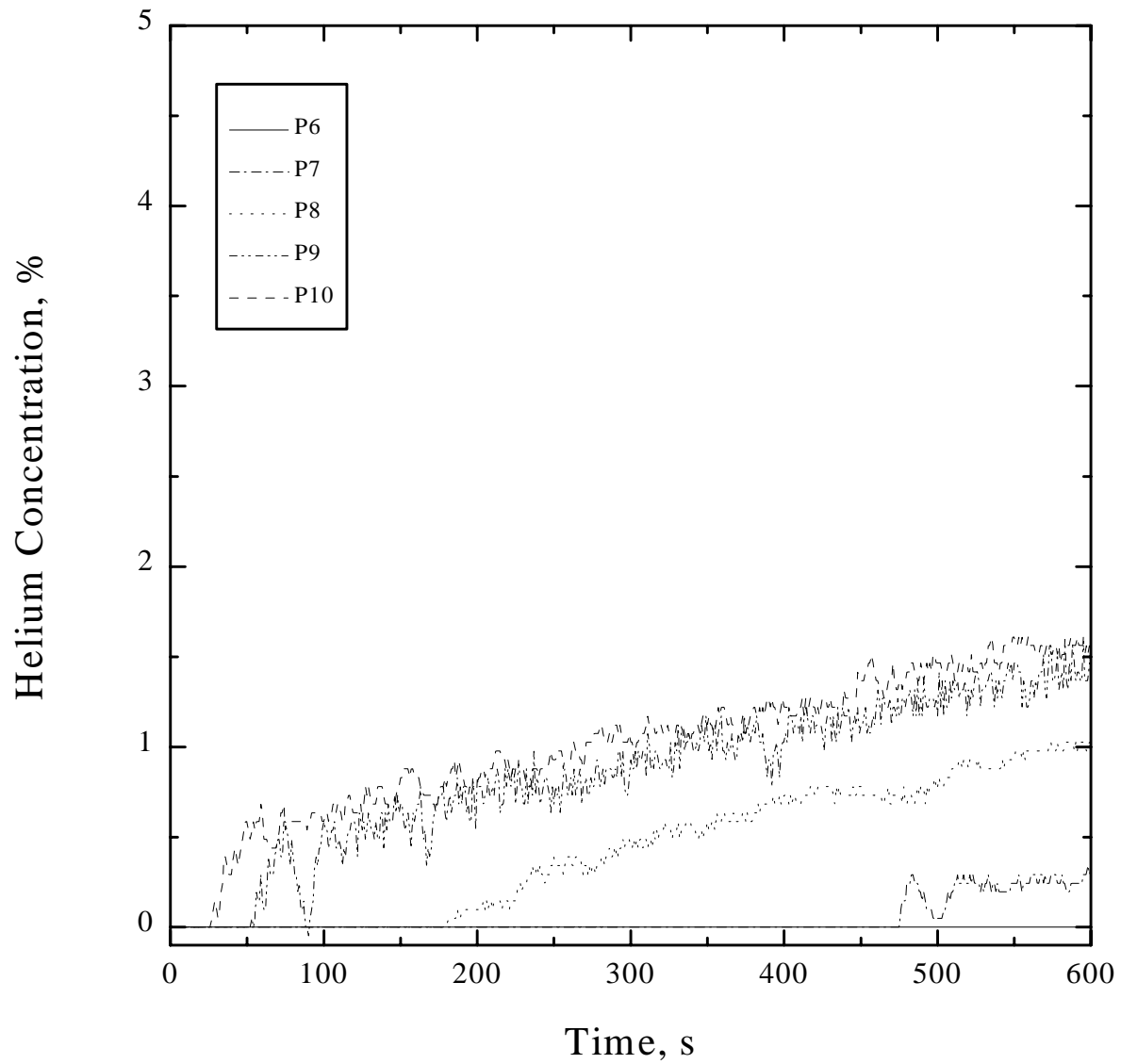


Figure 6: Concentration Measurements from Probes 6-10 for the Continuous Injection of Helium from the Bottom Inlet. (Jet diameter = 0.30 m; jet velocity = 0.24 m/s)

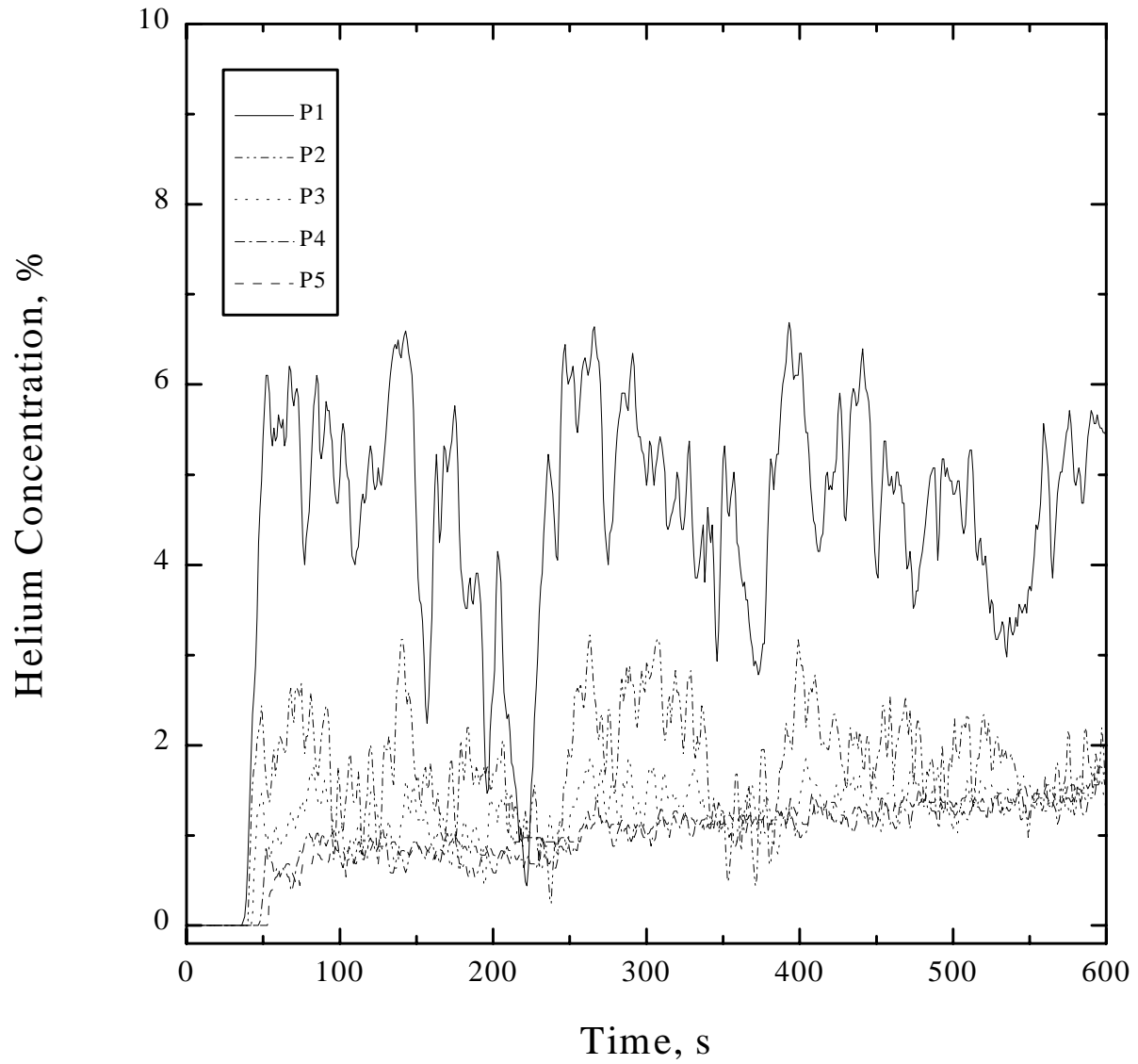


Figure 7: Concentration Measurements from Probes 1-5 for the Continuous Injection of Helium from the Bottom Inlet. A 1 m<sup>2</sup> horizontal plate was placed 0.45 m from the injection point. (Jet diameter = 0.05 m; jet velocity = 8.6 m/s)

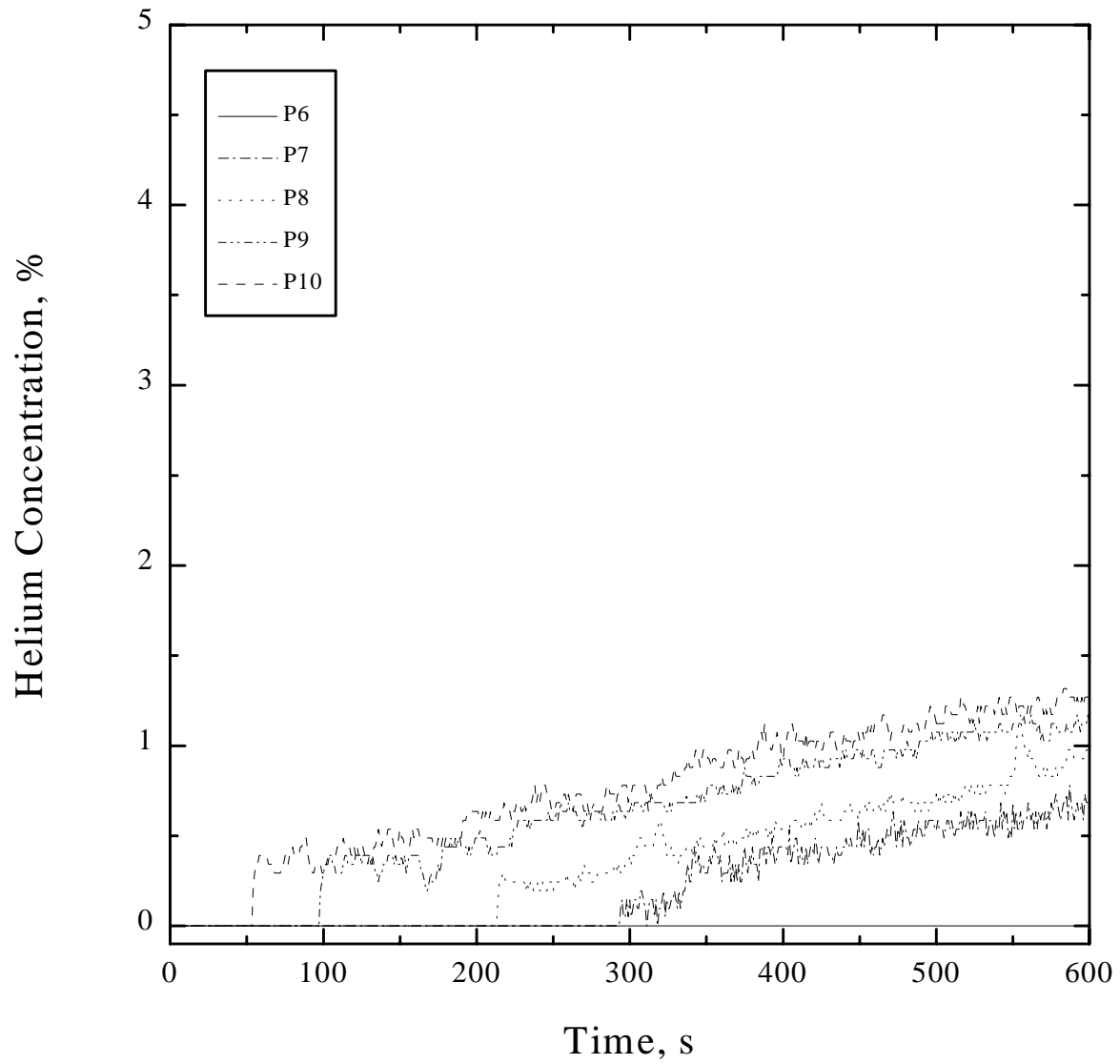


Figure 8: Concentration Measurements from Probes 6-10 for the Continuous Injection of Helium from the Bottom Inlet. A  $1 \text{ m}^2$  horizontal plate was placed  $0.45 \text{ m}$  from the injection point. (Jet diameter =  $0.05 \text{ m}$ ; jet velocity =  $8.6 \text{ m/s}$ )